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Navigation Strategy for the Mars 2001 Lander Mission

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The MSP 2001 project will send an orbiter, a lander, and a rover to Mars in the 2001 opportunity. The lander will demonstrate precision landing at Mars by utilizing improved approach navigation and hypersonic aeromaneuvering. The guided entry will result in a landed footprint that is an order of magnitude smaller than the Mars Pathfinder and Mars Polar Lander ballistic entry footprints. This paper will focus on improvements in interplanetary navigation that will decrease entry errors and will reduce the size of the landed footprint.

Introduction

The Mars Surveyor Program (MSP) is an ongoing series of robotic missions designed to perform global observations of Mars to enable a better understanding of the climatic and geologic history. These investigations include the search for liquid water and evidence of past or present life. The MSP 2001 project will advance the effort by sending an orbiter, a lander, and a rover to the red planet in the 2001 opportunity. The diverse science payloads on these spacecraft will allow the investigation of the Martian environment on both a global and on a local scale. Although this mission will not directly search for signs of life, it will demonstrate enabling technologies and science payloads that will be utilized by the future Mars Sample Return missions.

One technology that is needed for the Sample Return missions is the capability to place a vehicle on the surface within several kilometers of the targeted landing site. The MSP2001 Lander will take the first major step towards this requirement by demonstrating precision landing. Significant reduction of the landed footprint will be achieved through two technology advances. The first is improved approach navigation, and the second is hypersonic aeromaneuvering. It is anticipated that these precision landing techniques will produce a 3σ landed footprint that is only tens of kilometers, an order of magnitude improvement over the Pathfinder and Mars Polar Lander ballistic entries. This reduction will significantly enhance scientific return by enabling the selection of otherwise unreachable landing sites of unique geologic interest and public appeal. A landed footprint reduction from hundreds to tens of kilometers is also a milestone on the path towards human exploration of Mars, where the desire is to place multiple vehicles within several hundred meters of the planned landing site.

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This paper will focus on the interplanetary navigation strategy that will decrease entry errors and will reduce the landed footprint, even in the absence of aeromaneuvering. In addition to precise trajectory control, a robust strategy for communications and flight operations is needed. The resulting navigation and communications strategy utilizes optimal maneuver placement to take advantage of trajectory knowledge, minimizes risk for the flight operations team, is responsive to spacecraft hardware limitations, and achieves the desired entry accuracy.

Mission Overview

The MSP2001 mission will employ two launches during the 2001 opportunity. The orbiter spacecraft will be launched first on a Delta II 7925 launch vehicle from the Western Test Range at Vandenberg AFB in California. This flight marks the first time that a planetary spacecraft will launch from the West coast. The orbiter mission will utilize a twenty-day launch window opening in March of 2001. The orbiter will fly a Type I trajectory (less than 180° transfer) to Mars and arrive in late October of 2001.

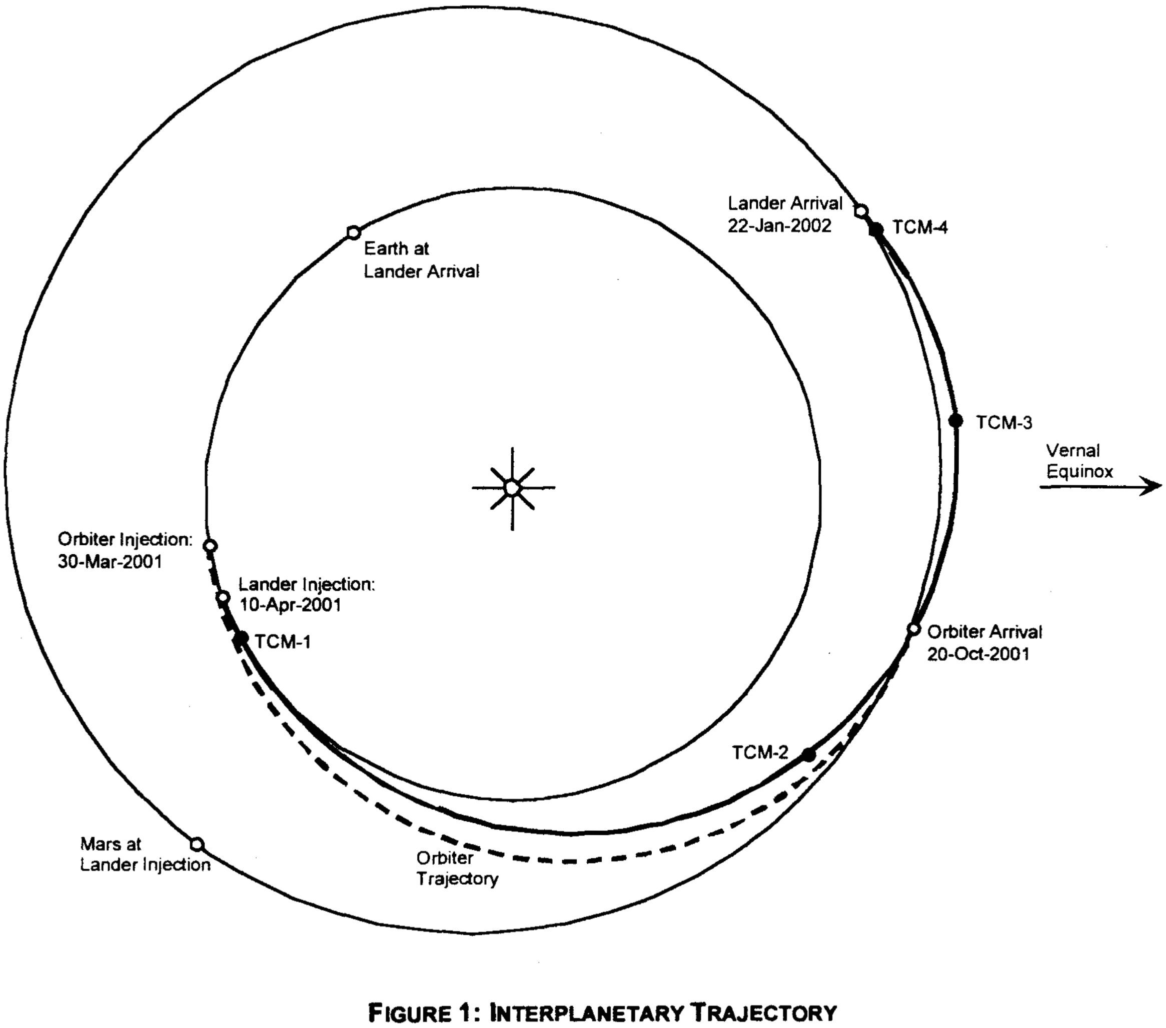

FIGURE 1: INTERPLANETARY TRAJECTORY

The lander mission will utilize a sixteen-day launch period that will open in April 2001 and will overlap the Orbiter launch window by several days. The lander package will utilize a Delta II 7425 and will launch from the Eastern Test Range at the Kennedy Space Center in Florida. The lander will fly a Type II trajectory to Mars and will arrive in late January of 2002.

The orbiter will arrive first and propulsively capture into approximately a 22-hour orbit about Mars. Aerobraking will then be employed to reduce the orbit period over the next 3 months. The vehicle will eventually stabilize into a 400 km circular, nearly polar orbit. When the lander arrives, the orbiter will act as a communications relay for the landed elements and begin science data collection. The orbiter mission is designed to last for three Martian years .

The lander spacecraft, consisting of the lander/rover package and a cruise stage, will arrive about three months after the orbiter. At encounter, the cruise stage will be jettisoned and the entry vehicle will perform a direct entry into the Martian atmosphere. Once the hypersonic entry phase is complete, the heat shield will be detached and the parachute deployed. The parachute phase will be unguided, and finally thrusters will be employed to soft-land the package on the Martian surface. Once on the surface, the refurbished engineering model of the Pathfinder rover named *Marie Curie* will be deployed to explore the Martian surface and will communicate through the lander. The Lander will not have a direct to Earth capability but will be able to communicate via a UHF link with the orbiter which will act as a communications relay. The landed mission is designed to last for ninety Martian days.

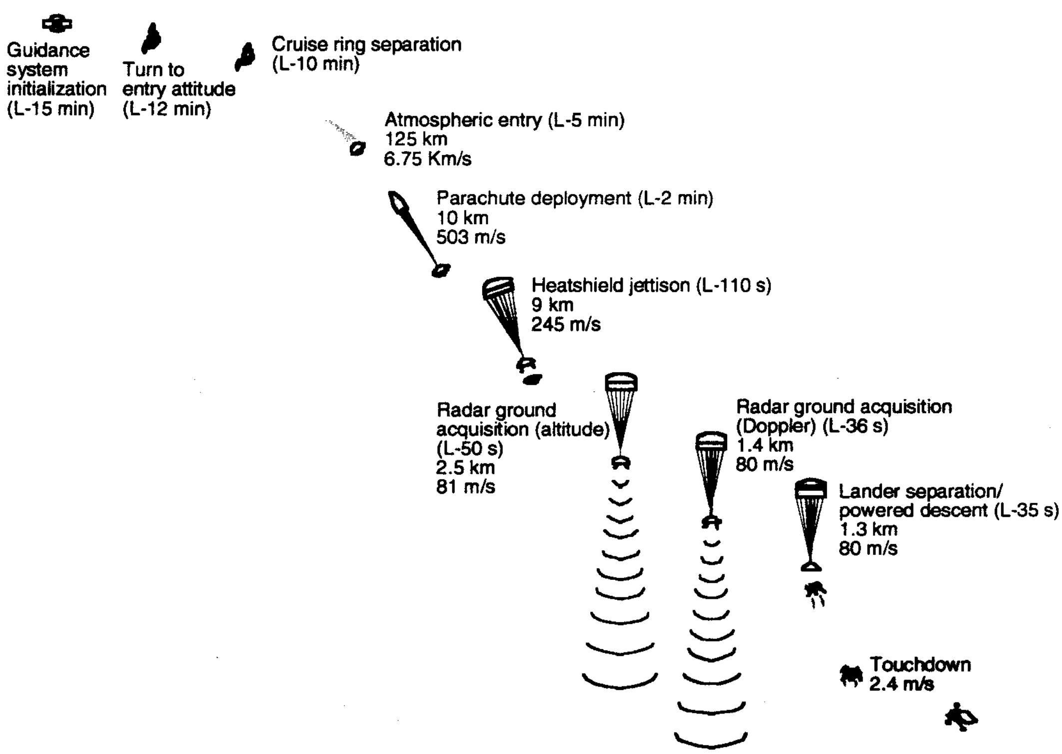

FIGURE 2: ENTRY, DESCENT AND LANDING

Although a specific landing site has yet to be chosen, the latitude band has been constrained to lie within 15° of the Equator. As will be shown later, the choice of landing site latitude will have a significant effect on the entry accuracy.

MSP2001 Lander

The design of the MSP2001 Lander is based in large part on the Mars Polar Lander. The lander structure has been strengthened to support the larger science payload, and flexible solar arrays are being developed to provide power in the stressful near-equatorial environment.

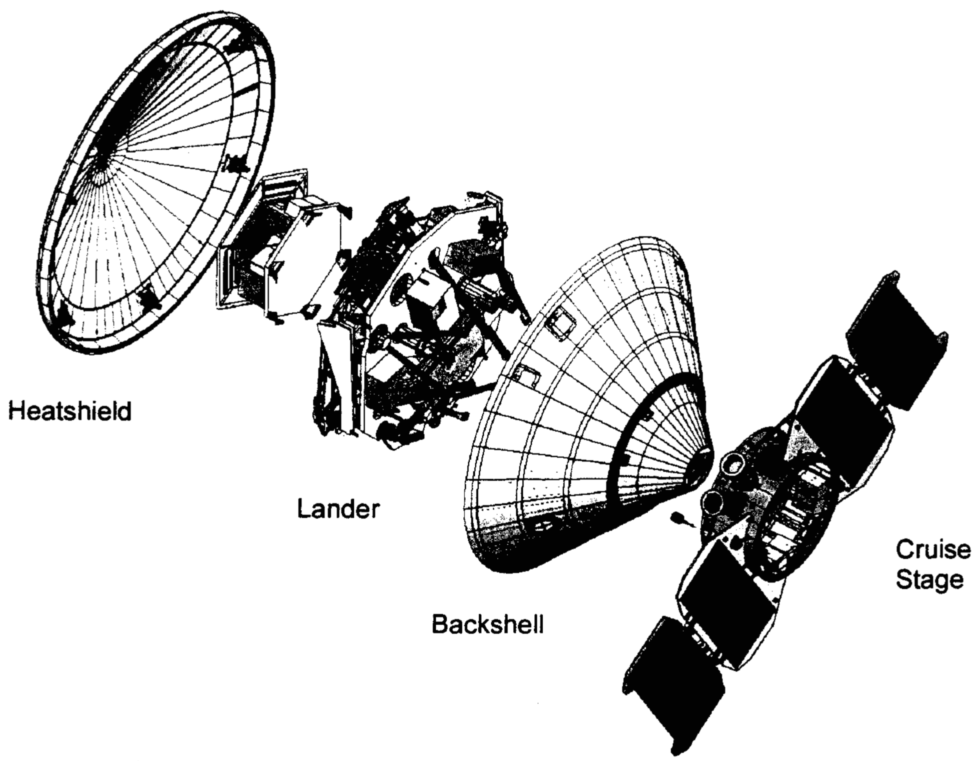

FIGURE 3: LANDER EXPLODED VIEW

The flight system consists of three major components: the cruise stage, the aeroshell (and backshell), and the lander itself. The cruise stage contains its own fixed solar arrays, an X-band telecom system including a medium gain antenna, and a GN&C system which consists of star trackers and sun sensors. The cruise stage is used for power and communications during cruise, and is jettisoned just prior to entry at Mars. The lander will be tightly packaged in a 2.65m diameter, aeroshell which is similar to that used for Viking, Pathfinder, and Mars Polar Lander. The aeroshell will protect the lander from the intense thermal environments it will encounter during EDL. The baseline aeroshell configuration is a Viking-derived forebody (70° spherically-blunted cone) with a conic afterbody. Such axisymmetric shapes can produce lift by flying at angle of attack, which is accomplished through a radial offset of the cg from the vehicle axis of rotation. This radial cg offset is achieved through efficient payload packaging or with ballast mass. The Lander propulsion subsystem is a pressure regulated mono-propellant system utilizing two high pressure helium tanks and two diaphragm equipped hydrazine tanks. The entire system is mounted on the lander, and the thrusters, called reaction engine assemblies (REAs), have a view to space through special holes in the backshell. The thrusters and the backshell form a close seal with each other to prevent atmospheric heating from damaging the lander.

The propulsion system provides for two distinct functions. The first function is to provide low thrust Trajectory Correction Maneuvers (TCMs) and cruise phase attitude control. This is provided by four 5 lbf TCM thrusters and four 1 lbf RCS thrusters. The 1 lbf RCS thrusters are used for primary attitude control during the cruise portion of the mission and are aligned such that they provide torque about all three vehicle axes. The 5.0 lbf TCM thrusters are primarily used to provide small velocity increments to the vehicle during the cruise portion of the mission.

The second major function of the system is that of final deceleration of the Lander for a soft landing on Mars. This is provided for by twelve 68 lbf thrusters divided into six groups of two located at three corners of the Lander to provide Pitch/Yaw/Roll control. The landing is accomplished with the system in full regulated mode.

Precision Landing

Significant improvement in targeted landings on Mars is necessary for future robotic and human exploration. Precision landing is the set of technologies that aim to reduce the size of the landed footprint, or targeting error. The landed footprint is a measure of how close the vehicle can be expected to land with respect to the target landing site, based on reasonable errors due to navigation and disturbances in the atmospheric flight. On the MSP2001 mission, this footprint reduction will be demonstrated through two technology advances; improved approach navigation, and hypersonic aeromaneuvering.

Improvements in interplanetary navigation will decrease entry errors and will reduce the landed footprint, even in the absence of aeromaneuvering. Improvement in the knowledge of the Mars ephemeris and gravity field have been gained from the previous Mars missions. Improvements in data collection and reduction techniques such as precision ranging and near-simultaneous tracking may also be utilized. Strategic maneuver placement will be the key to precise entry targeting. The Mars Polar lander will be the first demonstration of some of these techniques, and it is anticipated that they can be used to advantage by the future Mars missions.

Hypersonic aeromaneuvering is an extension of the atmospheric flight goals of the previous landed missions that utilizes an autonomous active guidance algorithm to control the aeroshell lift vector during the high dynamic-pressure portion of atmospheric flight. While numerous autonomous guidance algorithms have been developed for use during hypersonic flight at Earth, this will be the first flight of an autonomously directed lifting entry vehicle at Mars. The onboard guidance algorithm will control the direction of lift, via bank angle modulation, to keep the vehicle on the desired trajectory. Based on in-flight measurements of deceleration, the guidance algorithm can maneuver the vehicle towards a region of the atmosphere that is more or less dense, thereby accommodating off-nominal trajectory conditions or atmospheric flight conditions.

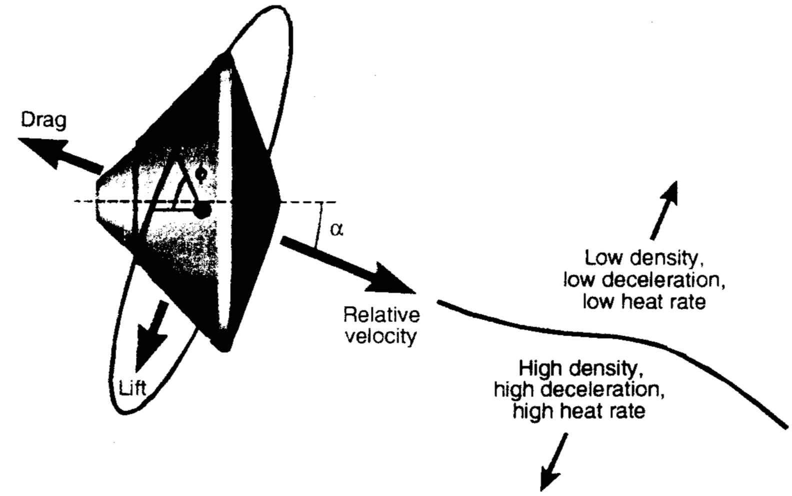

FIGURE 4: AEROMANEUVERING VIA BANK ANGLE MODULATION

Mars Pathfinder is the most recent example of a ballistic landing at Mars. The approach navigation was acceptable for the relatively benign targeting required, but the goal of the Mars Polar Lander and MSP2001 lander is to provide even better entry and landed accuracy. The anticipated landing ellipse for Pathfinder was on the order of 300 km (3σ) in semi-major axis (although the vehicle actually landed within 25 km of the targeted landing site). Better approach navigation on the Mars Polar lander will decrease its ballistic landed footprint to about 100 km (3σ). Even further improvement in approach navigation with the addition of aeromaneuvering on MSP2001 will result in a landed footprint of about 10 km (3σ) in semi-major axis.

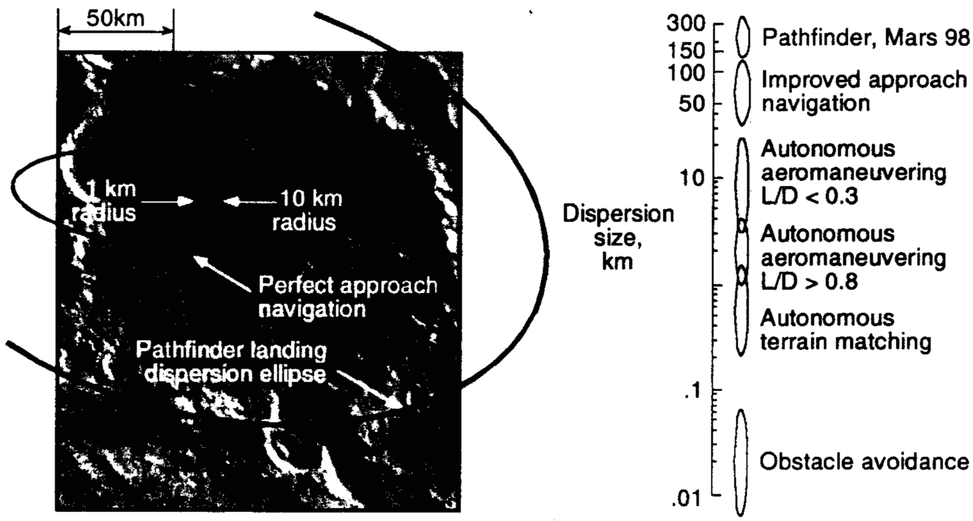

FIGURE 5: PRECISION LANDING TECHNOLOGY ROADMAP

Other precision landing techniques are envisioned for future missions and are currently being developed and tested on the Earth. Guided terminal descent, terrain recognition, beacon tracking, and active hazard avoidance are examples of the types of technologies that can be developed on Earth and eventually demonstrated at Mars. The Mars Polar Lander and MSP2001 Lander each have a descent camera that will image the Martian terrain during descent. Although these images will not be used for real-time guidance, the images can later be used to develop and test feature tracking and hazard avoidance techniques post-flight. It is these types of techniques that will be required to reduce the landed footprint to less than one kilometer. Thus, the precision landing technology will continue and improve beyond the demonstration planned for the 2001 mission.

Entry Corridor

The entry interface point is defined at a radius of 3522.2 km from the center of Mars. This radius represents the point at which significant atmospheric effects are expected to be sensed by the spacecraft. This reference is used for all simulations, and the inertial entry flight path angle target of -12.5° is defined at this interface radius.

The entry corridor is defined as an inertial flight path angle corridor that must be achieved at the entry interface radius. The requirement is to meet the –12.5° entry flight path angle with an accuracy of ±0.27° (3σ). The size of the entry corridor is limited on the shallow side by integrated heating constraints, and on the steep side by deceleration (g-load) and terminal descent propellant constraints.

The entry, descent and landing system performance is dependent on an accurate delivery to the proper entry flight path angle, as well as knowledge of the achieved FPA. So once the final maneuver has been executed, orbit determination activities will continue until atmospheric entry in order to predict and reconstruct the entry conditions as accurately as possible. These knowledge updates will be uplinked to the spacecraft just prior to entry to improve the performance of the on-board guidance algorithm. The requirement on the knowledge update is to predict the entry flight path angle to ±0.25° (3σ).

Although the ultimate goal is a small landed footprint, the interplanetary navigation strategy ends with the delivery to the atmospheric interface point. An accurate delivery will ensure a small landed ellipse. Once in the atmosphere, the vehicle is subject to atmospheric variations, as well as the guidance and control system during aeromaneuvering and powered descent. There will be no Earth-based navigation operations during this short but critical mission phase. Therefore, the remainder of this paper will focus on the delivery to the atmospheric interface radius, and meeting the constraints of the entry corridor.

Navigation Strategy

The final approach strategy is dependent not only on the navigation considerations necessary to achieve the entry corridor, but also on spacecraft hardware constraints during the final hours before entry. The placement of the final targeting maneuvers and the communications strategy will determine how accurately the lander can be delivered to the entry interface point and ultimately the size of the landed footprint.

For Mars Pathfinder and the Mars Polar Lander, approach navigation errors were the largest contributors to the size of the landed error ellipse. For the MSP2001 mission, the goal of the interplanetary navigation strategy is to deliver the spacecraft to the desired entry condition with sufficient accuracy and knowledge to enable satisfactory guidance algorithm performance. Specifically, the entry flight path angle must not exceed ±0.27° to a 3σ confidence level. This is a significant reduction relative to the ±1.0° Mars Pathfinder and ±0.45° Mars Polar Lander requirements. Entry errors contribute directly to the size of the landed footprint and the most significant component is entry flight path angle.

To meet the tight constraints on entry accuracy, it is necessary to schedule a maneuver (TCM-5) several hours before entry. At this time, the trajectory knowledge will finally be sufficiently accurate, and the effects of maneuver execution errors will be small. The drawback is that the entry accuracy is dependent on the success of this final late maneuver. Because propulsive maneuvers are critical events, it is desirable to minimize their occurrence and provide the flight team with as much response time as possible in the event of a spacecraft fault. A mission critical event less than one day before entry will not provide much fault tolerance, and it is desirable to provide a strategy that minimizes reliance on this maneuver. The maneuver cannot be completely eliminated, because the spacecraft trajectory will not be known to the required accuracy until the final day before entry. The timing of TCM-4 can be optimized however, to reduce the probability that TCM-5 will need to be performed.

Assumptions

A standard interplanetary navigation strategy is assumed for the spacecraft cruise to Mars. The spacecraft will make regular communications contacts with Earth that will provide 2-way X-band doppler and ranging data that can be used for orbit determination. During the last 45 days before Encounter, a 4-hours ON / 5-hours OFF telecom strategy will be employed that will provide near-continuous coverage of the lander on final approach. The spacecraft is scheduled to perform five trajectory correction maneuvers (TCMs). The first two correct for the upper stage planetary quarantine trajectory bias, and launch vehicle dispersions. The final three will correct remaining trajectory errors, and target the lander to its final entry aimpoint. Targeting accuracy is dependent primarily on trajectory knowledge and propulsive maneuver execution accuracy. Trajectory knowledge is a function of the orbit determination process, which is similar to other Mars missions. Maneuver execution accuracy is a measure of how accurately the spacecraft hardware can implement the desired ΔV for a given maneuver. Maneuver size also plays a role in execution accuracy model in that the implementation error is proportional to the magnitude of the ΔV. Therefore maneuver placement is also a prime consideration.

TABLE 1: MANEUVER PLACEMENT

	Relative Time	Description
TCM-1	Launch + 8 days	Correct injection errors and launch bias
TCM-2	Launch + 135 Days	Second of dual-maneuver optimization
TCM-3	Encounter – 60 Days	Correct TCM-2 execution errors
TCM-4	Encounter – 6 Days	Approach targeting
TCM-5	Entry – 7 hours	Final approach targeting

Determination of the spacecraft attitude during cruise will be achieved through the use of star trackers and sun sensors with an IMU used to propagate the attitude. The Lander attitude control strategy simply entails firing the RCS thrusters as needed to maintain attitude. This strategy is referred to as three-axis stabilization. This control strategy presents difficulties for the navigator as the thrusters fire almost continually and in random directions. However, for simulations and error analysis, the thrusting can be characterized as stochastic events that occur with a regular frequency.

The spacecraft engine hardware and the guidance system performance limit the accuracy of a desired maneuver. Errors in implementation can be characterized as errors in the magnitude of the maneuver and errors in the orientation or pointing of the thrust vector. These two error types (magnitude errors and pointing errors) can further be broken down into a fixed component and a proportional component. These error components (known as the Gates execution error model) have been calculated analytically by flight system engineers and are specific to the Mars '01 mission and hardware.

TABLE 2: MANEUVER EXECUTION ERROR MODEL

TCM ΔV Magnitude (m/s)	Fixed Magnitude Error (m/s)	Proportional Magnitude Error	Fixed Pointing Error (m/s)	Proportional Pointing Error
$\Delta V<0.3$	0.020 m/s	±2 %	0.003 m/s	±2 %
$0.3\leq\Delta V\leq 1.5$	0.020 m/s	±2 %	0.003 m/s	$\pm(8/1.2*\lvert\Delta V\rvert)$%
$1.5\leq\Delta V\leq 5$	0.020 m/s	±2 %	0.003 m/s	±10 %
$5\leq\Delta V\leq 20$	0	±2 %	0.003 m/s	$\pm((-8/15)*\lvert\Delta V\rvert+12.67)$%
$\Delta V>20$	0	±2 %	0.003 m/s	±2 %

For the orbit determination analysis, radiometric data are simulated based on the expected DSN communications schedule. Doppler data are weighted at 0.10 mm/sec (1σ, for a 60 sec count time), and ranging data are weighted at 3 meter (1σ). An epoch state batch filter is used to process the simulated tracking data. The epoch is chosen to be the time of injection and the epoch state is unconstrained. Estimated parameters include thrusting due to spacecraft attitude maintenance, trajectory correction maneuvers, and component reflectivities of the solar radiation pressure model.

Pass-by-pass stochastic range biases are estimated with an a-priori uncertainty of 5 meter (1σ) to account for station calibration errors and spacecraft transponder delay errors due to temperature variations. Media effects as well as Earth timing and polar motion parameters are also estimated stochastically. Station dependent range biases are estimated to account for Z-height errors. The strategy of estimating stochastic range biases as well as Earth motion and media effects has been termed precision ranging,

Knowledge of the Mars ephemeris has been significantly improved due to the successful MGS and Pathfinder encounters. The RSS position error has been reduced from approximately 50 kilometers down to less than ten kilometers (3σ). This assumption significantly improves the entry targeting capability compared to the Pathfinder mission.

All of these parameters are estimated in the OD filter, based on tracking data arcs of various lengths. The epoch is fixed at the injection time, and the data cutoff is taken to be five days prior to the execution of each TCM. This information will ultimately be used to determine how accurately each maneuver can deliver the vehicle to Mars. During the final days before entry, trajectory knowledge becomes quite important, as the final entry targeting strategy is dependent on precise trajectory determination. It will be shown that TCM-5 success cannot be guaranteed until the knowledge of the trajectory is better than the entry corridor constraint.

Results

The trajectory uncertainties are calculated at the time of the design of each TCM. The resulting error covariance is then mapped to the Mars-centered Mars Mean Equator of Date b-plane at the time of entry. The uncertainty is represented in the B-plane as a 2-dimensional error ellipse with associated semi-major and semi-minor axes and an orientation angle (Θ). The third component is represented as time-of-flight error. The knowledge update is a final chance to update the spacecraft inertial measurement unit (IMU) with the best estimate of the entry state before entry. This opportunity occurs about an hour before entry based on radiometric data collected after the execution of TCM-5. All data presented assumes a launch on the first day of the launch period. Data cutoffs are assumed to occur 5 days prior to TCM execution.

TABLE 3: OD KNOWLEDGE AT THE TIME OF EACH TCM (3σ)

	SMAA (km)	SMIA (km)	THETA (deg)	LTOF (sec)
TCM-1	1,791.9	301.1	39.6°	95.50
TCM-2	399.1	241.0	-61.5°	35.15
TCM-3	82.7	31.3	-61.4°	6.96
TCM-4	20.2	1.1	-62.3°	1.18
TCM-5	7.6	0.5	-68.1°	0.23
Knowledge update	6.8	0.3	-69.5°	0.18

SMAA - semi-major axis of the delivery ellipse (km)
SMIA - semi-minor axis of the delivery ellipse (km)
THETA - orientation of the delivery ellipse relative to the T-axis (deg)
LTOF - linearized time of flight (sec)

Although the trajectory knowledge is quite important, especially in the final days before entry, a more significant parameter in the navigation strategy is the delivery resulting from each TCM. The delivery describes how accurately the spacecraft can be targeted to the entry interface point. The delivery is determined by combining the trajectory knowledge uncertainty with the maneuver execution errors for each TCM in a monte-carlo simulation.

TABLE 4: TCM DELIVERY ACCURACY (3σ)

	SMAA (km)	SMIA (km)	THETA (deg)	LTOF (sec)
TCM-1	52,590	1,870	31.7°	2,685
TCM-2	7,263	3,261	33.4°	533.1
TCM-3	221.5	148.6	-43.0°	43.1
TCM-4	22.2	8.4	-61.8°	1.92
TCM-5	7.7	0.7	-68.0°	0.25

It is important to point out that the flight path angle error is a function of landing site latitude. The B-plane mapping remains the essentially the same regardless of latitude, however the projection of the uncertainty ellipse in the radial direction determines the flight path angle error. This projection is the uncertainty in the b-vector magnitude: |B|. It is evident that equivalent b-plane uncertainties map into significantly different b-magnitude and flight path angle uncertainties for the various different latitudes. Figure 6 presents the b-plane plot for both a 15° North latitude landing, and a 15° South latitude landing. Note that the delivery ellipses do not change in size or dimension, but the projection along the FPA (or radial) direction is significantly different. The uncertainty ellipses shown here are the actual TCM-5 delivery and knowledge update ellipses. The ±0.27° FPA corridor is represented as lines of constant b-vector magnitude.

For the trajectory geometry particular to this mission, it turns out that the FPA error is maximized at 15° North latitude, and minimized at 15° South latitude. As the landing site has not yet been chosen, the strategy is designed to accommodate the worst case: 15° North.

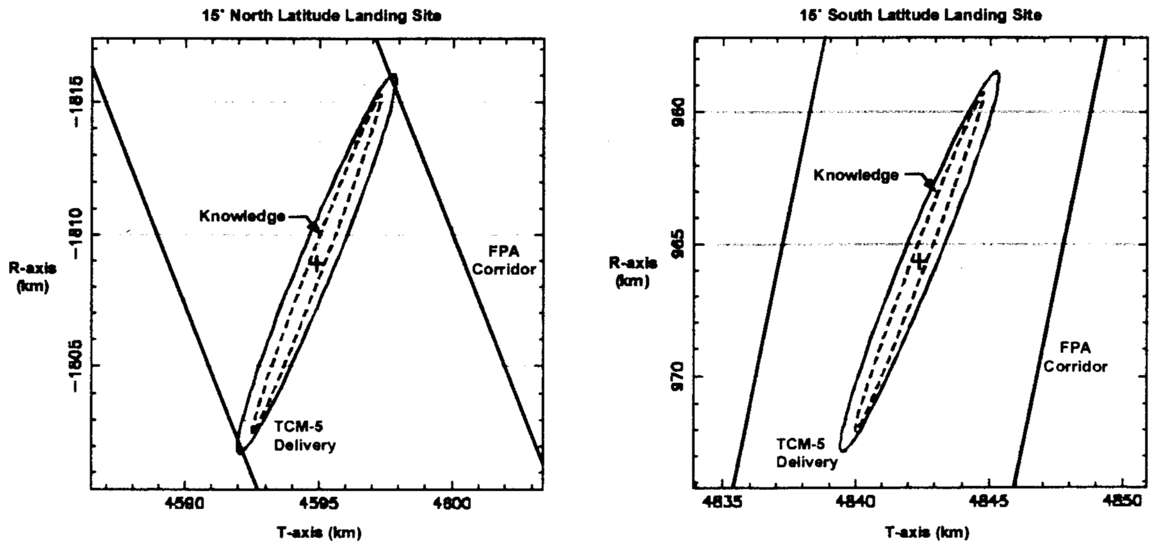

FIGURE 6: LANDING SITE LATITUDE DEPENDENCE

The delivery data can also be given in terms of FPA delivery uncertainty for 15° North, Equatorial, and 15° South landing latitudes. Only the final two maneuvers will be presented, as they are the only two that have the potential to accurately deliver the spacecraft to its target within the stated requirement. The flight path angle error is shown, along with the probability of achieving the FPA corridor. For this analysis, the corridor is defined as a FPA error of less than 0.27°, and it is assumed that TCM-5 will not be performed if the FPA error following TCM-4 is less than 0.27°. Maneuver delivery statistics are generated with a Monte-Carlo simulation, so it is a straightforward procedure to calculate the percentage of the samples that fall within the corridor.

Note that in all cases, the delivery resulting from TCM-5 meets the FPA corridor requirement. The stressing case is 15° North, and this is the case that drives the maneuver placement strategy.

TABLE 5: PROBABILITY OF ACHIEVING FPA CORRIDOR

	15° North	**Equator**	**15° South**
		3σ FPA Delivery	
TCM-4	0.93°	0.73°	0.54°
TCM-5	0.27°	0.19°	0.08°
		Probability of achieving the FPA corridor: % of samples < 0.27° FPA error	
TCM-4	58%	71%	83%
TCM-5	>99%	>99%	>99%

TCM-4 Placement

TCM-4 is placed at Entry – 6 days to maximize the probability that it will successfully deliver the spacecraft to the entry corridor. Figure 7 presents the probability that the delivery from TCM-4 will achieve the entry FPA corridor, and that TCM-5 would not need to be performed, as a function of maneuver time for three potential landing latitudes. Note that as the TCM is moved closer to encounter, the success rate increases, due to improvement in the trajectory knowledge and shorter time for propagation of maneuver execution errors.

However, as the maneuver moves closer, it statistically increases in magnitude. So at some point the large proportional errors associated with a larger maneuver outweigh the benefits of shorter propagation time. Originally schedule for Entry-10 days, the maneuver was moved in to increase the success probability. While it is desirable to have a high probability of success for TCM-4, it is not desirable to move it too close to encounter. Entry-6 days was chosen as a reasonable time for the maneuver, past which increasing success rate is not significant.

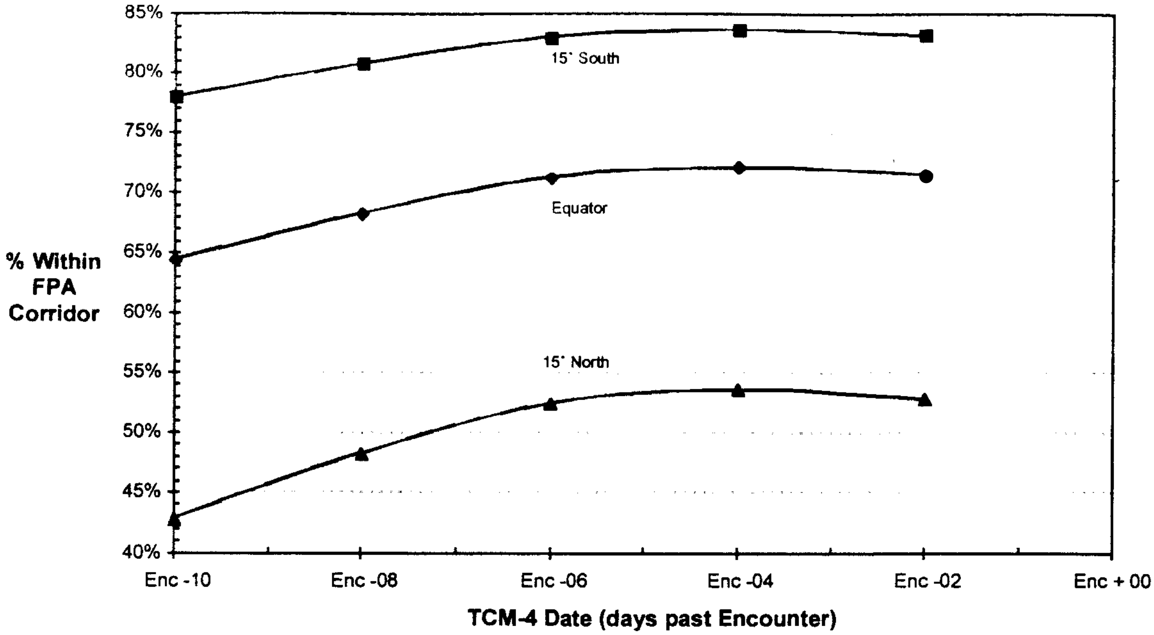

FIGURE 7: TCM-4 ACCURACY VS EXECUTION TIME

Despite these improvements, TCM-5 is still required. The best case provides less than an 85% probability for TCM-4 delivery success, which does not meet the 3-sigma project policy.

TCM-5 Placement

The approach timeline allows a final opportunity to target to the entry aimpoint and update the onboard guidance software with an estimate of the actual entry conditions. Nominally continuous contact with the DSN ground stations would provide sufficient coverage for all of these events. However, the spacecraft cannot generate sufficient power with the solar arrays to communicate continuously at this time. As a result, DSN contacts are specifically scheduled for tracking and uplink. At Entry-11 hours, a 4-hour track will collect the final radiometric data that will be the basis for the maneuver design. The next contact is primarily to uplink the final TCM sequence, with a 2-hour track following the TCM for maneuver reconstruction. The final short contact before entry is to uplink the updated entry conditions.

TCM-5 is placed at Entry–7 hours to provide a final opportunity to target to the entry aimpoint. As was demonstrated above, a maneuver placed at Entry–6 days will realistically provide up to a 80% probability of achieving the entry flight path angle corridor, but this does not meet the 3-sigma project policy. It is therefore necessary to wait until the trajectory knowledge improves to the point where a maneuver is guaranteed to achieve the corridor at the 3-sigma level. Figure 8 presents the flight path angle knowledge as a function of time on the last day of approach. Also shown is the DSN contact schedule, which indicates not only which stations are visible, but also when tracking data can be expected. For the 15° North landing latitude case, it is not until Entry-12 hours that the trajectory knowledge finally meets the ±0.27° corridor requirement. Entry-11 hours was chosen as the time for the data cutoff. The maneuver is designed and uplinked in four hours, and executes on the spacecraft at Entry-7 hours. In operations, if it is determined that the spacecraft trajectory is within the entry corridor after TCM-4, this maneuver would not be performed. These data suggest that there is not significant room to move the maneuver earlier in time and still guarantee a successful delivery within the ±0.27° corridor.

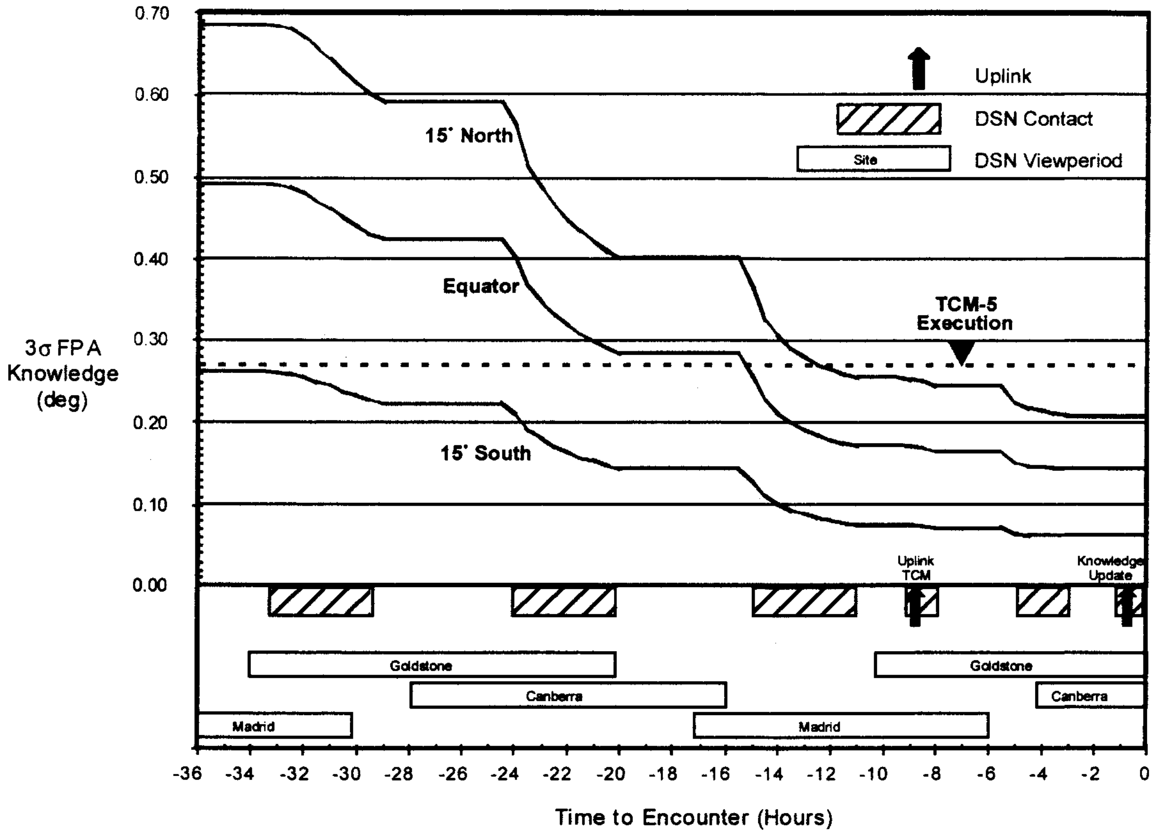

FIGURE 8: FINAL APPROACH STRATEGY

Time of day of entry is dependent upon the desired landed longitude. The scenario depicted in Figure 8 arbitrarily targets to a landing longitude of about 275° E. which corresponds to an entry at about 04:00 UTC. For this scenario, the DSN viewperiods are calculated, and happen to align nicely with the trajectory events. Entry occurs over a Goldstone-Canberra overlap, and the TCM uplink occurs over a Goldstone-Madrid overlap. This configuration is completely dependent on the time of day of entry (or landed longitude) and will not be known precisely until the final landing site is selected. Note that the trajectory knowledge on approach is sensitive to this geometry as well, and as the time of day of entry changes, the shape of the FPA knowledge curve will vary slightly.

One other point that is illustrated in Figure 8 is the TCM-5 uplink timeline (DSN contact #2). Note that there are two hours between the first uplink opportunity and the execution of the maneuver sequence. This provides margin to uplink, check telemetry to be sure that the commands were successfully received, and re-transmit if necessary. It is planned that the uplink will provide a tweak to maneuver parameters that are already stored onboard the spacecraft. This will help to minimize sequence generation time on the ground, and uplink time.

The other critical uplink is the entry state knowledge update that is provided to the spacecraft about 1 hour before entry. This contact will provide the guidance algorithm with the best estimate of the actual entry conditions. This information is important for the success and performance of the guidance system during the hypersonic entry phase. Again, sufficient time is scheduled to confirm that the commands are successfully received and to re-transmit if necessary. This uplink is also planned to be a tweak of onboard parameters to minimize sequence generation time on the ground. Note that for this geometry, both uplinks occur over a DSN station overlap, which provides additional fault tolerance to a single station being down.

Conclusions

The ultimate goal of the navigation strategy is to deliver the spacecraft successfully and accurately to the entry corridor. An important part of the strategy is to minimize the probability of performing a late TCM before encounter, thereby mitigating risk to the mission. Although the final targeting maneuver cannot be eliminated, there are options that will reduce the likelihood of performing it in operations.

The best option from an analysis perspective is to choose a southerly landing site. The flight path angle delivery error is minimized at 15° South. At this latitude, the final maneuver could even be moved farther away from entry and continue to meet the $\pm 0.27°$ flight path angle delivery constraint. In addition, TCM-4 has a better probability of delivering inside of the corridor than at more northerly latitudes. The drawback to this strategy is that the actual landing site has not yet been chosen, and it is undesirable, at this early date, to restrict the science community to a narrow landing latitude band.

The placement of TCM-4 has been chosen to maximize the probability of successfully delivering the spacecraft within the flight path angle corridor. While this strategy minimizes the chance of actually performing TCM-5, there are now two critical maneuvers scheduled in the final week before encounter.

Other possibilities, not presented here, are to further improve the maneuver implementation accuracy, further improve the orbit determination, or loosen the FPA corridor constraint. Hardware and cost are likely to limit further maneuver implementation accuracy. The FPA corridor is constrained by the Entry, Descent and Landing system performance. Larger entry dispersions imply a larger landed footprint, and larger required propellant usage for the terminal descent phase. Modest improvements could be expected in the orbit determination process with the addition of alternate data types such as near-simultaneous tracking or spacecraft-to-spacecraft ΔDOR. However, preliminary analysis of these strategies indicates that although the maneuver targeting would be more accurate, a final late TCM-5 would still be required. In this case, the modest benefits do not outweigh the implementation cost of these alternate data types.

The strategy as presented meets all of the project requirements, and minimizes risk where possible. The improvement in the interplanetary navigation strategy has been shown to decrease entry errors compared to previous missions and will reduce the expected landed errors, even in the absence of aeromaneuvering. In addition to precise trajectory control, a robust strategy for communications and flight operations has been developed. The resulting approach navigation and communications strategy utilizes optimal maneuver placement to take advantage of trajectory knowledge, minimizes risk for the flight operations team, is responsive to spacecraft hardware limitations, and achieves the desired entry accuracy.

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